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August 12, 1994

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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF SECRETARY

William F. Caton, Acting Secretary
Federal Communications Commission
1919 M. Street, N.W., Rm 222
Washington, DC 20554

Re: PR Docket No. 93-61, Ex Parte
Automatic Vehicle Monitoring Systems

Dear Mr. Caton:

On August 4, I was contacted by Mr. Richard B. Engelman, Chief, Technical Standards Branch, FCC Office of Engineering & Technology. Mr. Engelman conveyed to me an informal proposal developed by the Commission Staff for sharing of the 902-928 MHz band between Part 15 devices and systems providing automatic vehicle monitoring (AVM) and location and monitoring services (LMS), and requested written comments on the proposal by August 12. I hereby provide those comments and request that this correspondence be associated with the record of the above-referenced docket.

The Proposal

The proposal developed by the Commission is motivated by concerns that there will be interference between Part 15 devices and AVM/LMS systems that use multilateration to provide vehicle location services over wide areas. The Commission's proposal seems intended to strike a balance between protecting the interests of Part 15 devices and those of AVM/LMS operators. My understanding of the proposal, based on my conversation with Mr. Engelman, is as follows. Part 15 devices would operate throughout the entire 902-928 MHz band on a secondary basis as they do today. The bands 902-904 MHz, 910-920 MHz, and 926-928 MHz would be available for non-multilateration AVM/LMS systems (such as local-area "tag reader" systems). The bands 904-910 MHz and 920-926 MHz would be available for multilateration systems "exclusively" (meaning that non-multilateration systems would not be allowed in these bands). A Part 15 device operating in these multilateration bands would not be deemed a source of harmful

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interference unless at least one of the following "threshold" criteria is met:

1. It is an outdoor device with an antenna more than 5 meters above the ground.
2. It uses spread spectrum under §15.247 and radiates more than 6 dBW effective isotropic radiated power ("EIRP").
3. It is a field disturbance sensor operating under §15.245.

If a Part 15 device meets one or more of these criteria, and is causing interference to a multilateration system operating in either the 904-910 MHz band or the 920-926 MHz band, the Part 15 operator must work to resolve the interference in accordance with its secondary status. In the band 910-920 MHz, multilateration systems might be allowed on a secondary basis, and they would have no hierarchical superiority over Part 15 devices.

Comments

Although this proposal is an improvement over the "compromise" proposed jointly by some of the wide-area AVM/LMS interests,[1] it needs to be modified in several ways to properly balance Part 15 and AVM/LMS interests.

Interference from LMS to Part 15

Most of the concerns over Part 15 devices have heretofore focused on interference from Part 15 to LMS. This is largely due to the fact that most of the attention has centered on AirTouch Teletrac's system, since Teletrac is the Petitioner and is the furthest along among the wide-area AVM/LMS proponents in terms of system development and deployment. Teletrac's system does not pose a serious interference threat to most Part 15 devices, but seems to be relatively vulnerable to interference from them. Hence the focus on Part 15-to-LMS interference and the lack of attention to interference in the reverse direction.

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1. That proposal was conveyed in a letter to Ralph Haller, dated June 23, 1994, and was signed by AirTouch Teletrac, Pinpoint Communications, Inc., Uniplex, and MobileVision, L.P.

Recently, however, Pinpoint Communications, Inc. ("Pinpoint") has become highly visible in this proceeding, making numerous ex parte contacts and contrasting the design of its proposed ARRAY™ multilateration system with those of Teletrac and others. Significantly, Pinpoint proposes to use a denser network of base stations and much higher transmit power in the mobile than Teletrac, to achieve greater capacity (on the order of 1000-2000 locations/sec for Pinpoint vs. 70 locations/sec for Teletrac).[2] Pinpoint also proposes to use a wideband (12-16 MHz) forward link (base-to-mobile) rather than a narrowband channel (25 kHz) such as Teletrac uses. My calculations (shown in the Attachment) indicate that Pinpoint's proposed wideband high-power forward link could pose a serious interference threat to many Part 15 devices. Pinpoint's proposed system therefore highlights the need to incorporate measures in the final AVM/LMS rules to provide some protection from AVM/LMS interference for other users of the band.

One such measure would be the prohibition of wideband forward links. This should not impact the functionality of multilateration systems, since the forward link is essentially a paging channel and does not play a part in the actual locating function. Therefore, there is no inherent need for it to be wideband. In fact, as shown in the Attachment, the use of a wideband forward link is actually less efficient for the AVM/LMS operator in terms of spectrum and power utilization than a narrowband forward link, when the dominant impairment is interference from randomly-distributed transmitters such as Part 15 devices. It appears that the use of narrowband rather than wideband forward links would benefit all users of the band (see section V of the Attachment for details). Therefore, one restriction that should be added to the proposal is that high-power forward links used by multilateration systems be confined to narrow (e.g. 25 kHz) channels. In addition, some limitations should be developed for the transmitted power and the duty cycle of the mobile units transmitting on the wideband reverse links. Finally, there should be some reasonable limits on the transmit power (e.g. 30 watts) for non-multilateration systems in the 910-920 MHz band.

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2. As discussed in the Attachment to this letter, Pinpoint's high calculated capacity derives from its proposed mobile transmit power and base station density rather than its proposed bandwidth (12 to 16 MHz).

The Band Plan

Perhaps the best way to accommodate the forward links is to define twenty 25-kHz forward channels in the band 927.5-928 for forward-link operations.[3] One or several channels could be assigned for the exclusive use of each multilateration system operating in a given area. Because of the high-power nature of the forward link, there might be some benefit in leaving 927.0-927.5 as a guard band. Under this plan, Part 15 devices would still be allowed to operate in the 927-928 MHz band, but clearly would be subject to interference from AVM/LMS forward links. The impact of this on the band plan suggested by the Commission could be absorbed in several ways; if the bands 904-910 MHz and 920-926 MHz were intended to include the forward links, these bands could be reduced slightly.

Outdoor Antenna Elevations

The proposed 5-meter threshold outdoor antenna elevation threshold for "harmful interference" is not particularly meaningful from a technical perspective, and should be eliminated. While it is true that the path loss in general decreases as the transmitting antenna elevation increases, the exact relationship between path loss (and therefore interference potential) and antenna elevation depends on the local terrain features, including the heights of buildings (the antenna elevation above the building tops probably is more important than the elevation above the ground). Moreover, a criterion for antenna height relative to ground level is not particularly meaningful due to variations in local ground elevation. A more complicated antenna elevation criterion that accounts for all of the relevant factors, such as the height "above average terrain" computation specified in §90.309(a)(4), probably is impractical to administer in this case. The choice of an arbitrary antenna height threshold could result in a de facto elimination of many useful Part 15 applications, and should not be adopted.

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3. Locating the forward links, which typically transmit at power levels of at least several hundred watts, at the edge of the band will make them easier for some of the other band users to avoid. The upper band edge is particularly desirable because some devices in the 902-928 MHz band will require good front-end filtering at the upper band edge anyway, to protect them from paging signals at 929 MHz.

If there are any questions regarding this matter, please contact the undersigned.

Respectfully submitted,

Jay E. Padgett
Chairman, Consumer Radio Section
Telecommunications Industry Association

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Attachment:

"Wide Area Pulse-Ranging AVM/LMS:
Messaging/Locating System Design
Tradeoffs and Part 15 Interference"

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Attachment

WIDE AREA PULSE-RANGING AVM/LMS: MESSAGING/LOCATING SYSTEM DESIGN TRADEOFFS AND PART 15 INTERFERENCE

Dr. Jay E. Padgett
Chairman, TIA Consumer Radio Section
August 8, 1994

ABSTRACT

In PR Docket 93-61, the FCC has proposed to authorize the operation of systems providing automatic vehicle monitoring (AVM) and location and monitoring services (LMS) in the 902-928 MHz band on a permanent basis. There has been considerable debate in the Record of that Docket regarding several key technical issues. These issues include the appropriate band plan for wide-area, wideband pulse-ranging AVM/LMS systems and the potential for interference between those systems and Part 15 devices, which already are authorized to operate in that band on a permanent basis. Several significant misconceptions have developed regarding the tradeoffs among AVM/LMS system design parameters relating to these issues, making it difficult to assess the relative merits of the various proposals for the bandplan, power levels, sharing strategies, etc.

The purpose of this paper is to address those key issues by providing an engineering analysis of fundamental wide area AVM/LMS system design tradeoffs both with and without interference from "random" transmitters such as Part 15 devices. The conclusions that follow from this analysis are:

1. When the primary impairment is cochannel interference from transmitters that are randomly-distributed in location and frequency, such as Part 15 devices, the use of a wideband forward (base-to-mobile) link (as proposed by Pinpoint) is less efficient in terms of spectrum and power utilization than a narrowband channel (e.g. 25 kHz, as used by Teletrac). This conclusion (supported by

analysis in this paper) directly contradicts Pinpoint's claim that capacity increases with bandwidth when the dominant impairment is cochannel interference (rather than thermal noise). Moreover, a narrowband forward link is much more easily avoided by other users of the band than is a wideband link and therefore is preferable in a shared band such as 902-928 MHz.

2. For reverse (mobile-to-base) link bandwidths of interest in this Docket (4 MHz and up), the maximum locating capacity of a system (fixes per second) does not depend on bandwidth. Rather, the bandwidth determines the locating accuracy, and the maximum capacity depends on the power transmitted by the mobile and the spatial density of the base station receivers. Therefore, the bandwidth made available for reverse link operations should be based on the required accuracy rather than on capacity arguments. This conclusion is in disagreement with the claims of wide-area AVM/LMS interests that the maximum locating capacity increases quadratically with bandwidth.

3. Integration of the locating and messaging functions seems to be inherently spectrum-*in*efficient from both the locating and messaging perspectives. Whether this inefficiency is justified depends on the market demand for an integrated locating/messaging service compared to the demands for messaging and locating individually.

Given that AVM/LMS systems and Part 15 devices will share the 902-928 MHz band, these conclusions suggest a direction for wide-area AVM/LMS operating rules that should maximize the potential for the coexistence of these systems, both with each other, and with non-AVM/LMS services such as those provided by Part 15 devices:

- Wideband, high-power forward links should not be authorized, because they are inefficient from the perspectives of spectrum and power utilization and they pose an unnecessary interference threat to other users of the band. Multiple narrowband (e.g., 25 kHz) channels at the upper band edge should be designated for forward links. This will minimize the potential for interference (in both directions) between the AVM/LMS forward links and other users of the band. Each wide-area AVM/LMS service provider could be given exclusive use of one or several forward channels in a given territory.

- The availability of a relatively large block of spectrum (perhaps 8 to 16 MHz) for the reverse link may be justified on the basis of locating accuracy in the presence of multipath, with limits on the mobile transmit power and duty cycle. If necessary, a protocol for "time-sharing" of the reverse-link spectrum among multiple service providers coexisting in a given area could be developed cooperatively by the wide-area AVM/LMS interests, possibly under the auspices of a standards forum such as the TIA (Telecommunications Industry Association).

This framework should minimize the potential for interference between AVM/LMS systems and other users of the band, while allowing AVM/LMS system designers a relatively high degree of design freedom.

CONTENTS

WIDE AREA PULSE-RANGING AVM/LMS: MESSAGING/LOCATING SYSTEM DESIGN TRADEOFFS AND PART 15 INTERFERENCE

Dr. Jay E. Padgett
Chairman, TIA Consumer Radio Section
August 8, 1994

I. INTRODUCTION AND SUMMARY OF CONCLUSIONS

In PR Docket 93-61, the FCC has proposed to modify the current interim rules regulating automatic vehicle monitoring (AVM) systems in the 902-928 MHz band, and to allow systems providing AVM and "Location and Monitoring Services" (LMS) to operate in that band on a permanent basis. There has been considerable debate in the Record of that proceeding concerning some key technical issues related to AVM/LMS systems that use hyperbolic multilateration (HML) with wideband pulsed signals to provide a locating function over a wide area (e.g., a major metropolitan area). These issues include the appropriate bandwidth for wide-area AVM/LMS systems and the susceptibility of those systems to interference from Part 15 devices. There seems to be significant disagreement, especially with regard to the required bandwidth and the bandplan, among the four principal wide-area AVM/LMS interests: AirTouch Teletrac, Pinpoint, MobileVision, and Southwestern Bell Mobile Systems. The resulting confusion is compounded by the apparent lack of a clear understanding of fundamental system design tradeoffs relating to factors such as locating capacity (fixes/second/square km), messaging capacity (bits/sec/square km), base station density, transmitted power, RF bandwidth, data bits per locating pulse, etc. As a result, it is very difficult to make a reasonable assessment of the relative merits of the various proposals for the bandplan, power levels, sharing strategies, etc.

The purpose of this paper is to attempt to remedy that situation, at least partially, by quantifying the fundamental design tradeoffs and addressing several misconceptions that seem to have developed during the course of this proceeding. New analysis is introduced as necessary in pursuit of this objective.

The major conclusions are:

- For bandwidths of interest here (4 MHz or greater), the maximum locating capacity does not increase with bandwidth. Pinpoint and Teletrac have consistently maintained that the maximum capacity of a locating system (i.e., the number of location fixes per second) increases as the "bandwidth squared." As discussed in detail herein, for bandwidths in the range of interest in this proceeding (about 4 MHz to 16 MHz), increasing the bandwidth seems to allow ranging accuracy to be increased by permitting better mitigation of multipath, but does not allow the capacity of the locating system to be increased. The capacity depends on the base station density and the mobile transmit power. The large capacity claimed by Pinpoint for its proposed ARRAY™ system derives not from its bandwidth (12-16 MHz) but rather from its high-power mobile transmitters (40 watts) and its closely-spaced base stations.

- The use of direct-sequence spectrum spreading does not increase spectrum efficiency in an environment in which the primary impairment is cochannel interference from transmitters that are randomly-distributed in position and in frequency, such as Part 15 devices. In fact, as demonstrated here, widening the spectrum actually *disadvantages* a system operating in such an environment, despite the increase in processing gain. This result is in direct contrast to Pinpoint's claim that locating capacity increases as the "bandwidth cubed" when the dominant impairment is cochannel interference. The reasons for Pinpoint's erroneous conclusions are discussed.

- While the reverse (mobile-to-base) link must be relatively wideband (≥ 4 MHz) to provide acceptable ranging accuracy, the high-power forward (base to mobile) link, which is essentially a paging channel, should be narrowband (like that of Teletrac) and not wideband (like that of Pinpoint), for several reasons:
  - It does not need to perform a ranging function, so there is no inherent need for it to be wideband.
  - For the reasons discussed above, the use of a wideband forward channel is not a spectrum-efficient solution for the 902-928 MHz band.

- A high-power wideband channel has much greater potential to cause harmful interference to other users of the band (of which there are many) than a narrowband channel. Confining the high-power links to relatively narrow bands will allow other users to avoid them more readily.

- Multiple AVM/LMS service providers could be assigned their own forward link frequency bands. Assuming these bands are outside the wideband mobile-to-base link, this approach would seem to facilitate sharing among providers.

- Complete integration of the locating and messaging functions seems to be inherently inefficient from both the locating and the messaging perspectives. The messaging function is burdened with the need of the locating function to communicate with four or more base stations simultaneously, whereas a pure messaging function requires contact with only a single base at a given time. Thus, if the system is used primarily for a short messaging service, spectrum efficiency (bits per second per MHz per "cell") has been reduced more than fourfold (even ignoring the additional inefficiency, noted above, of using the wideband channel for transmission of a relatively low-rate data signal). Conversely, the locating function is burdened with the need to transmit many more pulses than would be necessary to perform a pure locating function. Pinpoint's proposed system uses 16 pulses, each containing 4 to 8 data bits. For the locating function in multipath, the benefit of more than a few pulses, in terms of improving accuracy, is questionable, and the need to transmit data appears to reduce the locating capacity significantly.

These conclusions are supported by detailed discussion and analysis in the body of this paper, which is structured as follows. Section II discusses ranging performance and bandwidth, both with and without consideration of multipath. Section III briefly discusses AVM/LMS system capacity for both the locating and messaging (data communication) functions. Section IV reviews the concepts of processing gain and jamming margin and discusses their application to the analysis of wide-area AVM/LMS systems, for both the locating and the messaging operations. Section V quantifies the AVM/LMS system design tradeoffs among bandwidth, transmitted power, service area, and capacity in the presence of interference from cochannel transmitters that are randomly-distributed in position and frequency. This analysis invokes a statistical model for the interference probability (derived in the Appendix) which accounts for the aggregate interference from multiple transmitters, rather than only a single transmitter. Section VI summarizes the conclusions, and based on those conclusions, outlines a recommended framework for FCC Rules to govern the operation of wide-area AVM/LMS systems in the 902-928 MHz band.

II. PULSE-RANGING PERFORMANCE AND BANDWIDTH

A. The Cramer-Rao Bound

For a receiver estimating the time-of-arrival (TOA) of a ranging pulse, the Cramer-Rao bound gives the lower bound on the TOA estimation error variance as:*

$$\sigma_t^2 \geq \frac{1}{2\beta^2 E_{RP}/N_0}\,, \tag{1}$$

where σ_t is the rms TOA estimation error, β is the "effective bandwidth" or "Gabor bandwidth" of the ranging waveform, E_{RP} is the energy in the ranging pulse, and $N_0/2$ is the two-sided noise spectral power density. If C is the received RF carrier (desired signal) power and T_{RP} is the duration of the ranging pulse, then $E_{RP} = CT_{RP}$.

The effective bandwidth β depends of the "shape" of the ranging waveform power spectrum as well as its occupied bandwidth; β^2 is essentially the second central moment of the signal spectrum, and β can be represented as $\beta = k_\beta B$, where B is the receiver noise bandwidth and k_β is a constant that depends on the shape of the signal spectrum.

In general, multiple ranging pulses can be used and the individual TOA estimates averaged to give a composite estimate. If n pulses are used, the variance of the error in the composite estimate will be reduced by a factor of n compared to that of each individual estimate. Assuming that the performance of an actual receiver tracks the

* See, for example, M. Skolnik, *Introduction to Radar Systems,* Second Edition, New York: McGraw-Hill, 1980.

Cramer-Rao bound but with some fixed offset (in dB), then the actual TOA estimation error can be expressed as:

$$\sigma_t^2 = \frac{k_R}{2nk_\beta^2 B^2 E_{RP}/N_0}, \tag{2}$$

where k_R is a constant that depends on the receiver implementation; clearly, $k_R \geq 1$. For example, if $k_R = 2$, then the receiver operates 3 dB above (worse than) the Cramer-Rao bound. It should be noted that (2) applies only when E_{RP}/N_0 exceeds some threshold, denoted here by χ_{RP}. If E_{RP}/N_0 falls below χ_{RP}, the receiver no longer operates in accordance with (2).

On the surface, (2) suggests that there is a tradeoff between B and nE_{RP}, assuming other system parameters are fixed, and given some target value of σ_t. Since $E_{RP} = nCT_{RP}$ and "capacity" (number of location fixes per second) varies inversely with nT_{RP}, the location capacity seems to vary as B^2 as has been repeatedly observed by AVM/LMS interests.* This relationship requires that $E_{RP}/N_0 > \chi_{RP}$ (i.e., the receiver must be operating above threshold). Therefore, as T_{RP} is decreased, transmitter power must be increased to maintain the necessary margin (which assures that the probability that $E_{RP}/N_0 < \chi_{RP}$ is acceptably small, given such real-world uncertainties as the variation of the received signal due to "shadow fading").

It has been shown that when the receiver threshold is taken into account, the "bandwidth squared" capacity increase claimed by Pinpoint and Teletrac based on the Cramer-Rao disappears.† Pinpoint does not seem to have understood the analysis; in

* See, for example, p. 10, Exhibit A of Pinpoint's June 29, 1993 Comments on the Notice of Proposed Rule Making (NPRM) in PR Docket 93-61, entitled "The relationship between Position-fixing rate & Occupied Bandwidth in AVL Systems," Louis Jandrell, VP Design & Development, Pinpoint Communications, Inc. See also p. 21, Appendix 1 of Teletrac's June 29, 1993 Comments on the NPRM, entitled "Analysis of Cochannel Pulse-Ranging Systems," Professor Raymond Pickholtz.

† "Analysis of Teletrac receiver performance and Part 15 interference," J. E. Padgett, *Ex Parte* presentation associated with PR Docket 93-61, October 22, 1993.

its Reply Comments on the *Ex Parte* presentations, Pinpoint states:

> The TIA analysis mistakenly posits a system operating near threshold levels. Practical AVM systems would not be designed to operate at or near the threshold because variances in propagation path loss are so large that if a system were designed to run at the threshold level, it would be operating below the threshold level most of the time.*

Pinpoint is correct that in the mobile radio environment, a "margin" typically must be factored into the link budget to account for path loss variations due to shadow fading. For example, assuming lognormal shadow fading with $\sigma = 8$ dB, a shadow fade margin of about 10 dB would correspond to a fade probability of 10% on a circular boundary representing the nominal edge of coverage. In other words, if the radius of the circle is such that the *median* received signal is 10 dB above threshold, then there is a 10% probability that the signal will drop below threshold for a mobile on the circle. In mathematical terms this means that if M is the fade margin in dB and $m = 10^{M/10}$, then the edge of coverage is defined such that the median received signal strength is $CT_{RP} = m\chi_{RP}N_0$, or $T_{RP} = m\chi_{RP}N_0/C$. Clearly, if T_{RP} is reduced without either increasing the transmitted power or reducing the operating area, the margin will be compromised and the fade probability will increase. The point is that for an "apples-to-apples" comparison of two systems, the fade margins must be equal. With equal margins, it is easy to see that there is no capacity increase regardless of the bandwidth. If T_{RP} is reduced in order to increase capacity, then either the transmitted power must be increased or the service area must be reduced in order to maintain the margin.

To put the discussion in more concrete terms, an example is worthwhile. Teletrac's receiver, with a bandwidth of roughly 4 MHz, operates in accordance with the relationship σ_r (feet) $\simeq 2/\sqrt{C/N}$, where $N = BN_0$ is the thermal noise power and the C/N threshold is about -25 dB.† The rms ranging error therefore is roughly 35 feet when the receiver is just at threshold. Assuming the same performance relative to the Cramer-Rao bound (roughly a 5 dB offset in this case) and the same spectral shape

* Pinpoint Communications, Inc., Reply Comments on the *Ex Parte* Presentations, PR Docket 93-61, filed March 29, 1994, p. 30, footnote 63.

† J. E. Padgett, *op. cit.*

for the signal (i.e., k_R and k_β fixed), the variation of σ_r in feet with bandwidth at the receiver threshold can be expressed as $\sigma_r \simeq 140/B$ (MHz). Note that as B increases, N increases proportionally, but as long as C and T_{RP} are fixed, E_{RP}/N_0 remains constant. Assuming that the E_{RP}/N_0 threshold does not change, the C/N threshold varies inversely with B; i.e., the "jamming margin" (discussed in section IV) increases linearly with B. Hence, with C and T_{RP} constant, the receiver continues to operate at threshold as B increases. For a 16 MHz bandwidth, therefore, $\sigma_r \simeq 9$ feet when the receiver is operating at threshold. If a 10 dB margin is assumed, then the median σ_r becomes 11 feet for $B = 4$ MHz and 2.8 feet for $B = 16$ MHz, at the nominal coverage edge.

For the capacity of the 16 MHz system to be 16 times as great as that of the 4 MHz system, the received power for the 16 MHz system must be 12 dB higher than that for the 4 MHz system, to maintain a median E_{RP}/N_0 10 dB above threshold at the edge of coverage. This requires some combination of higher transmitted power and a smaller coverage area. If the transmitted power remains constant, the coverage area (the area for which the median E_{RP}/N_0 exceeds the threshold by 10 dB) by definition will shrink. For example, if median path loss varies as the fourth power of distance, the area will shrink by a factor of four. It is interesting to note that in this case, the number of locations/second/MHz/km^2 has remained constant (but four times as many base stations are needed).

It might be argued that for systems with excess margins, a variation of capacity with bandwidth does in fact exist. To illustrate, assume that the 4 MHz system is over-engineered so that there is 12 dB of excess margin in E_{RP}/N_0 (the median E_{RP}/N_0 is 22 dB above χ_{RP}, so the median σ_r is 2.8 feet at the nominal coverage edge). Capacity could be increased sixteen-fold by reducing T_{RP} by a factor of 16, thereby reducing the median E_{RP}/N_0 to 10 dB above χ_{RP} and increasing the median σ_r to 11 feet. Clearly, the median σ_r can be reduced back to 2.8 feet by increasing the bandwidth to 16 MHz. However, because of its excess margin, the capacity of the original 4 MHz system could be increased sixteen-fold without increasing the bandwidth, by merely allowing the median σ_r to be 11 feet rather than 2.8 feet at the nominal coverage edge. A reduction in the median σ_r from 11 to 2.8 feet seems to be well past the point of diminishing returns and does not seem to justify increasing the bandwidth from 4 MHz to 16 MHz.

The point is that for a bandwidth on the order of 4 MHz or more, the accuracy of the receiver ranging estimate in the absence of multipath is so good even when the receiver is operating near its threshold that further bandwidth increases are irrelevant. As a result, there is no practical capacity increase with bandwidth even when reduction in the system link budget margin is allowed (i.e., an "apples-to-oranges" comparison). As will be seen in the next subsection, bandwidths larger than 4 MHz may be justified for reduction of multipath-related errors, but the multipath mitigation benefits of bandwidth increases beyond 4 MHz do not translate into increased capacity.

B. Ranging Accuracy vs. Bandwidth in Multipath

As just shown, (2) suggests that extremely accurate ranging should be possible with bandwidths on the order of 4 MHz or more. In practice, ranging estimates with the indicated accuracy are not normally achievable due to multipath, which the Cramer-Rao bound and (2) do not take into account.

It is well-known in communications that the use of wideband signals and correlator-based receiver techniques allow multipath components to be resolved, and that the achievable time-resolution varies inversely with the signal bandwidth.* It is reasonable to expect that wideband signals would also offer advantages in combatting multipath effects for ranging functions. While this does not appear to have been studied as extensively as multipath mitigation for communications applications, Pinpoint states that "A ranging resolution of approximately 100 feet requires that multipath echoes be resolved to within a similar level. To achieve this requires a bandwidth of between 15 and 20 MHz ((1.5 to 2)/(100 nanoseconds)), depending mainly on implementation tradeoffs." † This suggests that if e_m represents the ranging error due to multipath, then $e_m \sim k_m/B$ (MHz), where e_m is the ranging error in feet and k_m is between 1500 and 2000. Fig. 1 shows the corresponding bounds on ranging error, along with the rms ranging error based on the extrapolation of Teletrac's receiver performance discussed above, and $n = 1$ (a single ranging pulse). Assuming

* See, for example, J. G. Proakis, *Digital Communications,* New York: McGraw-Hill, 1983, chapter 8.

† Louis H. M. Jandrell, Vice President - Design and Development, Pinpoint Communications, Inc., in a written *Ex Parte* presentation filed May 11, 1994 in association with PR Docket 93-61, p. 2.

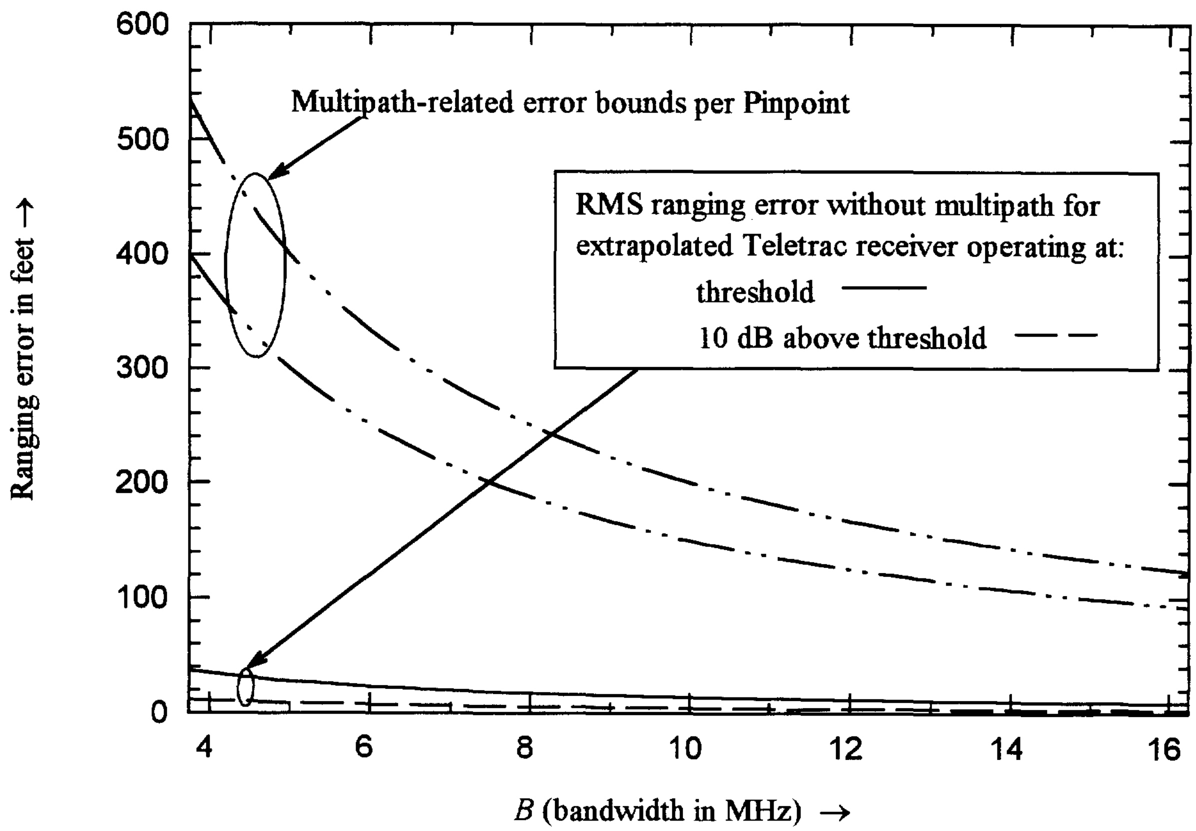

Figure 1. *Ranging accuracy vs. bandwidth, with and without multipath.*

that Pinpoint's relationship between bandwidth and the multipath-related error is valid over the range of bandwidth shown, it is clear from Fig. 1 that the ranging error is dominated by multipath. Since multipath is self-interference, the ranging error will be essentially independent of E_{RP}/N_0, as long as $E_{RP}/N_0 > \chi_{RP}$. Thus, assuming the receiver is operating above its threshold, the ranging error is essentially a function of bandwidth alone (for a given receiver implementation). This reinforces the conclusion that there really is no inherent increase in locating capacity as bandwidth is increased. The bandwidth determines the ranging accuracy, and capacity is determined by the minimum T_{RP} that will maintain E_{RP}/N_0 above the receiver threshold with the necessary margin.

Another implication of the dominance of ranging errors by multipath is that the mean-squared ranging error may not vary inversely with n, the number of ranging pulses factored into the TOA estimate. In the Gaussian noise case (no multipath) to which the Cramer-Rao bound and (2) apply, the receiver in theory gives an *unbiased* estimate of the actual range. This means that if r is the actual range and $\hat{r}$ is the receiver's estimate of r, then $E[r - \hat{r}] = 0$.* The rms range estimation error is simply $\sigma_r = \sqrt{E[(r - \hat{r})^2]}$, which (in feet) is very nearly the same as the TOA estimation error in nanoseconds. In the multipath case, the propagation path of even the first resolvable "ray cluster" to reach the receiver typically is longer that the actual distance between the transmitter and receiver. If this excess distance is denoted by δ (obviously a non-negative random variable), then $E[\hat{r}] = r + E[\delta]$; i.e., the estimator is no longer unbiased. If the duration of the n ranging pulses is short compared to the channel coherence time,† then the bias introduced by the excess propagation path length will be relatively unaffected by averaging the results of n estimates.

In sum, the ranging accuracy (and therefore locating accuracy) of a wideband pulse-ranging AVM/LMS system is limited by multipath, and that accuracy appears to improve as bandwidth is increased. It is clear that the capacity of a system for the *locating* application (in fixes per second per square mile), as opposed to the *messaging* application, is not related to the system bandwidth, for bandwidths in the range relevant to the discussion in PR Docket 93-61 (4 MHz and greater). Further, range estimates are unlikely to be improved significantly by multiple repetitions of the ranging pulse, unless they occur over a time exceeding the channel coherence time. That coherence time will typically be on the order of 10 milliseconds or more, depending on the vehicle speed, so averaging may not be very practical from a capacity perspective. Of course, multiple fixes for a number of vehicles could be interleaved over several seconds, but this would introduce additional latency into the system and tend to complicate the "bookkeeping," especially for a high-capacity system.

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* The notation $E[\cdot]$ denotes the expected value, or statistical average, of the argument (which is a random variable).

† The coherence time of the channel is inversely related to the maximum Doppler frequency of the channel, which for a mobile radio channel, depends on the carrier frequency and the speed of the vehicle. For a frequency of 915 MHz and a vehicle speed of 60 mph, the maximum Doppler shift is about 82 Hz, so the coherence time is on the order of 10 millisec. For a lower vehicle speed, the coherence time will be greater.

III. SYSTEM CAPACITY FOR RANGING AND MESSAGING

A. Locating Capacity

For the locating application using hyperbolic multilateration, the system must be designed such that $E_{RP}/N_0 \geq \chi_{RP}$ with an acceptably high probability at a minimum of two receiver pairs. If thermal noise is the only impairment, N_0 is fixed, so the requirement on an individual receiver is that $CT_{RP} \geq \chi_{RP} N_0$. Since maximum capacity varies inversely with T_{RP}, it is immediately clear that the capacity is proportional to C, the received RF power. Assuming that the limiting factor is the mobile-to-base link, ranging capacity therefore is controlled by two factors: (1) the power transmitted by the mobiles, and (2) the density of the base stations. This conclusion seems to support the claimed capacity of Pinpoint's proposed system (1000-3000 locations/sec) compared to that of Teletrac's system (70 locations/sec). Pinpoint proposes to use a transmitted power of 40 watts in the mobile units, while Teletrac's mobile units transmit 5 watts with an antenna "gain" of -6 dBi, so the effective radiated power (ERP) is 1.25 watts. In addition, Pinpoint's proposed base station density is greater than that of Teletrac. Clearly, Teletrac could increase both its mobile transmit power and its base station density to increase capacity.

B. Messaging Capacity

Messaging is a data communication function, and the performance vs. bandwidth tradeoffs for the different digital modulation formats are well-known. If E_b is the energy in an information bit and T_b is the duration of a bit, then $E_b = CT_b$. An acceptable bit error rate (BER) requires that $E_b/N_0 > \chi_b$, where χ_b is a threshold that depends on the modulation, the receiver, the required BER, and baseband digital signal processing such as forward error correction (FEC); i.e., channel coding. Fig. 2 shows the "bandwidth efficiency" (ratio of the bit rate to the required bandwidth) for various types of digital modulation, and the E_b/N_0 required to deliver a bit error probability of 10^{-4} and 10^{-6}. Coherent detection without channel coding was assumed. The "16-orth" and "256-orth" points represent "M-ary" orthogonal signaling formats with $M = 16$ and $M = 256$ (orthogonal signaling is of interest for combined ranging/messaging applications and is discussed more extensively in section IV). Biorthogonal signaling would double the bandwidth efficiency. As $M \rightarrow \infty$ $(1/BT_b \rightarrow 0)$ for orthogonal or biorthogonal signals, the required E_b/N_0 approaches

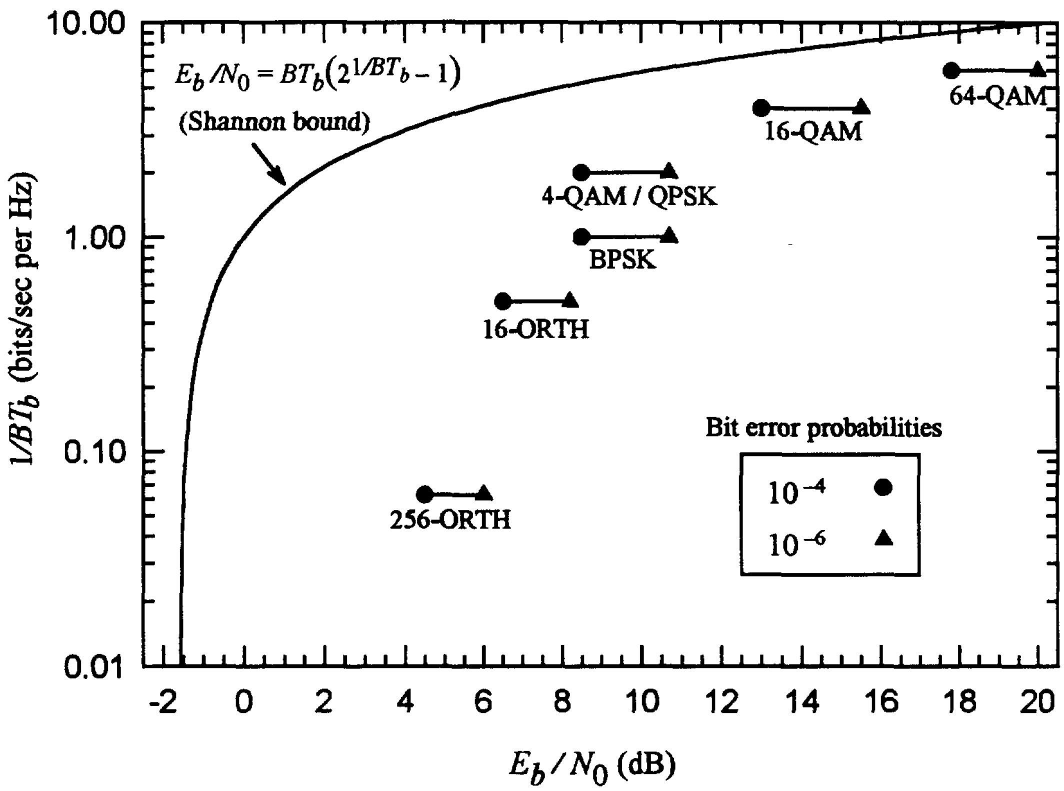

Figure 2. *Bandwidth efficiency vs. E_b/N_0 for various modulation formats with coherent detection and no channel coding.*

the Shannon bound. For all the modulation formats, performance can be moved closer to the Shannon bound by using channel coding, at the cost of additional bandwidth and transceiver complexity.

It is clear that for a given modulation format, the maximum bit rate determines the required bandwidth, as well as the received signal power. Therefore, like the locating capacity, the messaging capacity depends on transmitted power and base station density. For a system that combines locating and messaging functions by embedding data in the ranging pulse, the number of ranging pulses used determines the number of bits in a data message (i.e., a packet).* Thus, while the use of multiple ranging

* The design/performance tradeoffs related to embedding multiple data bits in a ranging pulse are discussed in detail in Section IV.

pulses may be of marginal value for the locating function, it may be essential for messaging applications. For example, if each ranging pulse includes 4 data bits and a packet is 8 bytes (64 bits), then packet requires the transmission of 16 ranging pulses.

C. Combined Ranging and Messaging

A system that combines both the locating and messaging functions by embedding data in the ranging pulse requires design compromises to both functions. The locating capacity is reduced by the need to transmit multiple pulses. The messaging capacity is reduced by the need to maintain an acceptable communication path to at least two pair of base stations, whereas a pure messaging application would require contact with only a single base station. Moreover, if the dominant impairment is expected to be interference from other band occupants, then an additional capacity price is paid due to the need to spread the spectrum on the mobile-to-base link for the ranging application (this effect is discussed in detail in Section V). These conclusions contrast sharply to Pinpoint's assessment of its proposed ARRAY™ system. In its Comments on the *Ex Parte* presentations, Pinpoint states: "Because the system accomplishes messaging while it performs ranging, no additional spectrum is required. This raises the overall throughput of the ARRAY™ system relative to one that performs ranging and sends data sequentially in the same bandwidth."* The second statement appears to be untrue, since without the ranging function, the data rate could be increased by decreasing T_b, because communication with only a single base station is required (and therefore $E_b/N_0 = CT_b/N_0$ could be decreased). Data could be transmitted to a single base, then ranging achieved with only one or a few pulses, since the ranging function would no longer be burdened with the need to carry data.

In sum, the capacity for both locating and messaging (data communication) is proportional to received power, which in turn depends on the transmitted power of the mobile units (assuming that the reverse link is the limiting factor), and the density of the base stations. The bandwidth determines the locating accuracy, and also

* Comments of Pinpoint Communications, Inc. on *Ex Parte* presentations, p. 3 of Exhibit B, entitled "Discussion of Factors Affecting Throughput in Wide-Area AVM Systems," Louis H. M. Jandrell, Vice President of Design and Development, Pinpoint Communications, Inc., March 15, 1994.

determines the data rate, given the number of chips per data bit (the processing gain). If the locating and data capacities are defined in terms of fixes/sec/km^2 and bits/sec/km^2, respectively, then increasing the base station density can also allow increased frequency reuse over a large metropolitan area, further increasing capacity.

IV. PROCESSING GAIN, CHIP RATE, AND JAMMING MARGIN

A. Review of Direct Sequence Spread Spectrum Systems

Wideband pulse-ranging systems use a form of direct-sequence (DS) modulation to generate the wideband ranging signal. In a basic DS communication architecture, the baseband data stream is encoded onto a high-rate pseudorandom or "pseudonoise" (PN) sequence, which is modulated onto the RF carrier and transmitted. The receiver correlates the incoming signal with the specific chip pattern of the transmitted PN sequence, and the demodulated correlator output is input to the detector (decision circuitry), which recovers the baseband data. A "processing gain" is realized in the receiver because the correlation between interfering signals (or noise) and the PN sequence is low, and the correlation process greatly reduces the effective noise and interference into the detector. The correlation function generally is implemented in one of two ways: (1) using a surface acoustic wave (SAW) correlator; or (2) using a pure digital correlator, in which case the received signal would be down-converted to a manageable intermediate frequency (IF), digitized, and processed digitally.

B. Basic Relationships

The "bits" of the PN sequence are usually referred to as "chips," and the duration of a chip is denoted here by T_C. The signal bandwidth is proportional to the chip rate $(1/T_C)$, so:

$$B = \frac{k_{BT}}{T_C}, \tag{3}$$

where k_{BT} is a design-dependent constant on the order of 1; its exact value depends on the pulse-shaping of the spreading waveform (and hence the shape of the RF signal spectrum) as well as the receiver IF frequency response.

If the DS system is used to transmit data at a rate of R_b $(= 1/T_b)$ bits/sec, then the energy per bit is $E_b = C/R_b$. The total RF noise power is $N = BN_0$, since by definition B is the noise bandwidth. Thus,

$$\frac{E_b}{N_0} = \frac{B}{R_b} \cdot \frac{C}{N} . \qquad (4)^*$$

The "processing gain" often is defined as:

$$G_P = \frac{B}{R_b} = \frac{k_{BT}}{R_b T_C} . \qquad (5)$$

Therefore, if k_{BT} is 1, the processing gain is simply the ratio of the chip rate $(1/T_C)$ to the bit rate. Given the E_b/N_0 threshold χ_b discussed above, the requirement for acceptable messaging performance is:

$$G_P \frac{C}{N} \geq \chi_b . \qquad (6)$$

The "jamming margin" for data communication is the maximum N/C for which the BER is acceptable, and can be expressed as:

$$M_{JD} = \frac{1}{(C/N)_{MIN}} = \frac{G_P}{\chi_b} . \qquad (7)$$

For example, with a spreading factor of 1000 chips/bit, $G_P = 30\,\text{dB}$. If $\chi_b = 10\,\text{dB}$,

* It is noteworthy that (4) is a general relationship; its applicability is not limited to spread-spectrum systems.

then $M_{JD} = 20\,\text{dB}$, which means that the system can still receive data with an acceptable BER with the desired signal 20 dB *below* the noise (and interference). While this is the classical definition for the jamming margin of a DS data communication system, a jamming margin can also be defined for the ranging function using:

$$\frac{E_{RP}}{N_0} = BT_{RP} \cdot \frac{C}{N}, \tag{8}$$

which gives:

$$M_{JR} = \frac{k_{BT} T_{RP} / T_C}{\chi_{RP}}. \tag{9}$$

Note that the use of n ranging pulses in the locating burst *does not* change the processing gain or jamming margin, since each pulse is separately correlated, as discussed below. This directly contradicts a statement made by Hatfield Associates on behalf of Pinpoint, which claims that "the overall processing gain is nearly equal to the number of chips in the transmitted sequence times the number of correlator outputs that are averaged together." Hatfield Associates then proceeds incorrectly to compute the jamming margin based on this definition of processing gain.*

C. Implementation Issues and Wideband Receiver Techniques

A discussion of wideband DS system performance would not be complete without considering the receiver architecture. Although direct-sequence spreading *per se* does not reduce the threshold χ_b, the wideband nature of the DS system does provide the opportunity for receiver techniques which can reduce χ_b, at the cost of additional

* Exhibit 1, p. 3 of Pinpoint's March 29, 1994 Reply Comments on the *Ex Parte* presentations, entitled "Response to MobileVision's 'Technical Review' ".